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Earth-Satellite Propagation Research

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Slant-path propagation research is contributing to technical developments and business growth in new satellite-communications applications.

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Earth-space propagation research in the United States is tied to new developments in satellite communications. In spite of the fiber optics competition for trunked point-to-point communications, a host of emerging services are taking advantage of the great potential of satellites for wireless communications. The use of satellites in radio communications appears to be increasing rapidly in the areas of mobile/personal and thin-route (low-traffic) applications.

The congestion of the spectral slots at K_u and lower bands¹ is an important factor in satellite communications. The heavy use of this spectrum gives rise to conflicts among users and occasionally forces regulatory organizations to relocate frequency assignments — a decision that, for obvious reasons, is unpopular with the relocated service. The 1992 World Administrative Radio Conference (WARC '92) was held in Torremolinos, Spain, in early 1992 to consider reallocating the electromagnetic spectrum for a host of new communications technologies. As a result of WARC '92 decisions, some established radio systems residing in the reallocated bands may have to be moved if new systems cannot share frequencies without interference. For example, the 13.75-14.0 GHz band was reallocated to the Fixed-Satellite Service (Earth-space). This in turn caused the National Aeronautics and Space Administration (NASA) to move the operating frequency of its scatterometer from 13.9995 GHz to a lower frequency, at considerable cost.

Because of a radio spectrum shortage below about 17 GHz, frequencies in K_u and higher spectral bands are seen as good candidates for Earth-space communications in the future.

New challenges in propagation research include the characterization of mobile/personal links and the investigation of higher bands for satellite communications. An example of the radiowave propagation scenarios mentioned previously is illustrated in Fig. 1. In the figure, the mobile terminal, with a low-gain antenna, operates in frequencies

below 10 GHz and is faced with propagation anomalies caused by shadowing, Doppler, and multipath effects. The fixed terminal, with a high-gain antenna, operates at frequencies above 10 GHz and suffers from atmospheric effects.

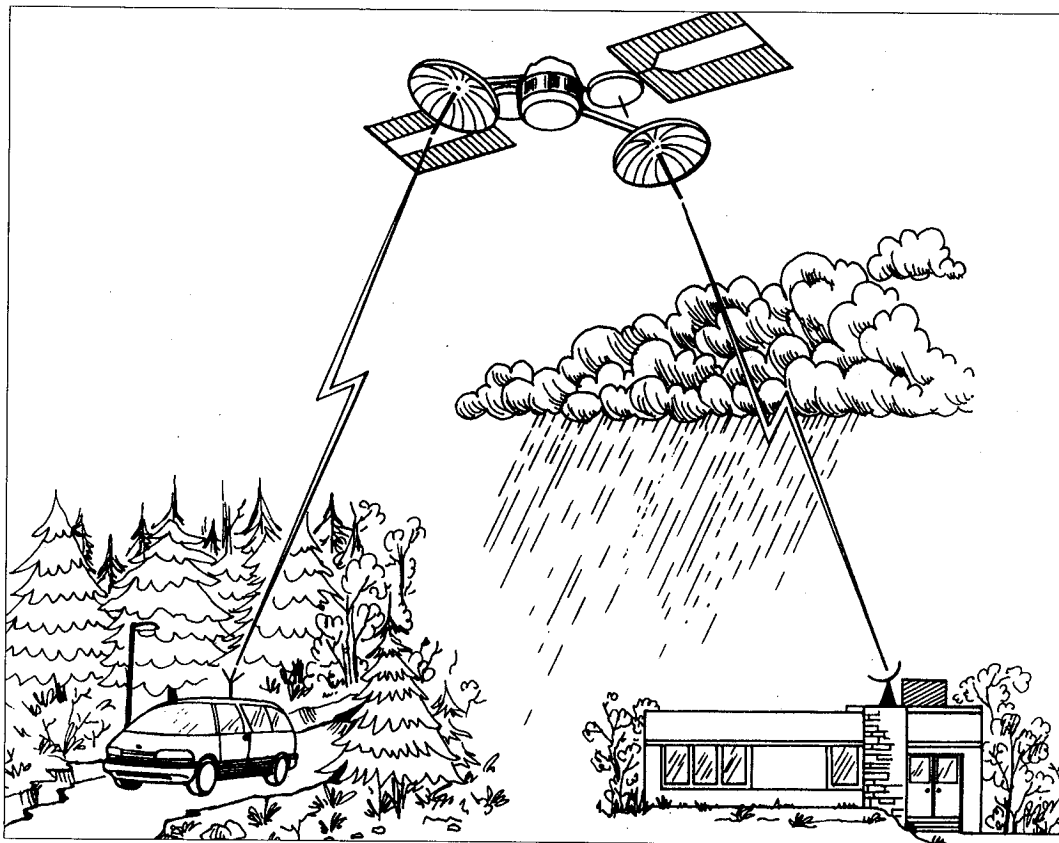
Mobile and Personal Applications

The world's first operational land mobile satellite system will soon begin voice and data service in Australia [1]. The use of satellites for mobile communications, however, is not a new idea. Initial investigations took place in the 1970s, and a major effort was carried out in the 1980s in NASA's Mobile Satellite Experiment (MSAT-X) at the Jet Propulsion Laboratory [2]. It was soon realized that a good understanding of the channel characteristics is fundamental to the planning of mobile satellite systems. To support the MSAT-X and the emerging mobile satellite technologies, the NASA Propagation Program funded a number of studies to examine the propagation effects of land mobile satellite channels. In addition to analytical work, these efforts included a considerable number of field measurements. In the early years of the endeavor, data was collected by using simulated space platforms, such as balloons and helicopters [3], and more recently, satellite transmissions [4, 5]. The mobile experiments in the U.S. were conducted primarily at UHF and L-bands, and they employed primarily omnidirectional ground antennas. Studies conducted in the U.S. assumed a geostationary satellite orbit.

It is worth noting that, in parallel with NASA's efforts, propagation researchers in other countries also investigated the vagaries of the mobile satellite channel. Notable efforts took place in Canada [6], Europe [7], and Japan [8]. Work on nongeostationary systems was reported by European researchers [9]. Some of these investigations included aeronautical and maritime mobile satellite links [10, 11]. A compendium of results for land

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¹ Because there is no worldwide standard on band designators, the author loosely defines frequencies from 12-30 GHz as K-band. The first portion of this band, 12-17 GHz, is called K_u and the rest is called K_a .



■ Figure 1. Radiowave propagation in earth-space links.

mobile satellite systems can be found in [12], and two recommendations from the International Telecommunications Union's (ITU) Radiocommunication Sector² address propagation in aeronautical and maritime mobile satellite systems [13].

Three recent events have influenced the future of mobile/personal applications. First, in the '80s, Voice of America recognized the value of satellites in direct radio broadcasting to augment the less-reliable short-wave broadcasting [14]. More recently, the commercial use of the direct satellite broadcast radio (DBS-R) has attracted much attention both in the U.S. [15] and abroad [16].

Second, many potential service providers have lately considered the use of satellites for personal communications [17-21]. Much attention is now being given to low-earth-orbit (LEO) satellite applications as well as geostationary-earth-orbit (GEO) applications.

Third, the WARC '92 addressed mobile/personal applications and opened new regions of the spectrum for them. Although the L- and S-bands are presently the most popular spectral slots, allocations as low as 150 MHz³ and as high as 30 GHz exist for slant-path mobile/personal applications, and most of these frequencies are likely to be used sometime in the future.⁴

The task facing propagation researchers is the characterization of a vast region of the spectrum for mobile/personal links. This assignment is particularly challenging because the mobile channel behaves in a nonstationary manner. Mobile/personal receivers may operate in a variety of propagation environments, including reception with or without a clear view (tree shadowing, blockage). In addition to the above effects, the Doppler-induced

dynamics of the signal must also be taken into account.

Data availability is currently limited to a few selected frequencies with only a limited number of physical and environmental attributes; therefore, future efforts should concentrate on expanding the existing propagation database to all the bands of interest and include a broader selection of environmental parameters. It is also important that a diversity of satellite orbits GEO, LEO, and highly elliptical orbit (HEO) be considered in the future studies. This is a partial list of topics in propagation research that needs to be performed:

- Conduct propagation measurements into buildings to determine the spatial, spectral, and temporal signal structure for indoor reception.
- Perform mobile measurements in urban, suburban, and rural environments to derive statistical information, determine model parameters, and obtain data for channel simulation. Measurements through trees must receive attention. Improved methods for describing and specifying the local environment are needed.
- Make stationary and mobile measurements of the delay spread to model the wideband behavior of mobile/personal channels. Sites in city centers and mountainous areas are of special interest.
- Develop service contour maps that depend on such parameters as frequency, orbit, land environment, and coverage area.
- Develop a systematic method for evaluating ITU-allotted spectral slots for different applications.
- For applications near equatorial regions, information is needed on the morphology of ionospheric scintillation at low latitudes, particularly as it affects L- through C-bands, because these

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² Previously known as CCIR.

³ Several newly formed telecommunications companies in North America are planning to use frequencies slightly below 150 MHz for LEO transmissions.

⁴ L-band refers to frequencies between 1 and 2 GHz. S-band refers to frequencies between 2 and 4 GHz.

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bands will soon be used by DBS-R and aeronautical services.⁵

- To enhance system performance, propagation effects should be mitigated or reduced. Examples are adaptive coding, power control, and smart antennas that can adapt their performance to match the propagation characteristics of the channel (multipath reception).

In addition, land mobile satellite service providers need detailed statistics on regions of interest to them. However, the collection of detailed information on all the regions of interest will be prohibitively expensive. The following is a good compromise:

- Optical blockage and shadowing measurements should be made to provide statistics on a given environment, such as a given region, a particular highway, and so forth. Optically based sensing systems can predict radio propagation impairments resulting from signal blockage and shadowing [22].

The above studies should also address the effect of polarization and antenna type.

In the future, the designers of mobile/personal satellite-based networks are likely to employ simulation schemes for system design and evaluation applications. Therefore, propagation data and models are needed to develop simulation tools. For such applications, time-series data or data generated locally using known signal statistics can be used. Future propagation research should support the development of simulation tools.

Rain and Cloud Effects

Most rain attenuation-prediction procedures depend on rain climate models. Most available climate models are now about 15 years old, have not been updated in a consistent way to incorporate new observations, and are not dependent on measurable parameters such as annual and monthly rain accumulation, the number of days with rain, and synoptic conditions to be associated with rain. Once the relationship between rain attenuation model and measurable climatological data is known, maps of the latter can be used to generate maps of the expected attenuation to be exceeded for a given fraction of time on a specific type of path such as from a mobile vehicle to a geostationary satellite. Future propagation research should include a revision of current rain climate models, similar to the work conducted by Crane [23]. Furthermore, rain-rate distribution models should be expanded to represent seasonal behavior of the rain process. The annual/worst-month distribution relationships depend on the seasonality of the process, as do any models developed to explain the variability of the process.

Because most of the available data have been or will be used to provide the parameters for model distributions, more samples are needed to provide an independent data set to test the models. Samples should include the rain rate distributions for locations where observations have been made, as well as data for new locations.

An important component of most rain attenuation models is the rain height, which is dependent on variables in geographic regions (latitude and longitude, season, and storm type). Although the rain height is not always equal to the 0° isotherm

height, it is often associated with the altitude of the 0° isotherm out of convenience. Simultaneous radar and attenuation observations have demonstrated that when the precipitation is stratiform, optimum agreement is obtained for heights corresponding to the 0° isotherm [24]. However, dual-polarized radar measurements have shown that the above statement is not valid for convective rain [25]. In general, rain height statistics are best obtained by combining dual polarization radar observations with beacon measurements [26].

For many applications the assumption of a fixed rain height is not realistic; therefore, statistics on the variation of rain height with day, season, time of day, location within a storm, and other factors are needed. For applications such as aeronautical mobile, the stochastic approach to rain height modeling is imperative. It is also important for receiver terminals in mountainous areas.

Some rain attenuation models depend on the expected correlation between rain rates at different locations along a path. An improved model for the correlation structure of rain rate can be useful for such applications.

By ignoring the microstructure of rain, the available models give rise to errors in signal attenuation prediction and discrepancies in frequency scaling. These problems become more important for frequencies above about 17 GHz, because of the sensitivity of these frequencies to changes in the drop size distribution at the smaller drop sizes. A basic problem lies in the difficulty of making reasonable drop size distribution measurements. Employing measurements at the higher frequencies (the 90- and 120-GHz windows) simultaneously with measurements at lower frequencies may unravel this problem. Rain drop size distribution can also be measured by radars and disdrometers [27, 28]. Efforts to improve and simplify disdrometer measurement techniques should be considered. The microstructure problem is one that affects the performance of real-time "frequency scaling," an important component of the uplink power control problem.

Although the influence of clouds can be ignored for the lower frequencies, their effect is important at higher frequencies. Multifrequency radiometers, similar to the ones operated by the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, are practical and a relatively inexpensive means of cloud sensing [29]. Because radiometers cannot determine the atmospheric liquid water versus distance, data from other remote sensing measurements may need to be combined with radiometric data for cloud modeling. Clouds may be characterized with high-power, high-resolution radars operating at the longer wavelength, such as the S-band or C-band. Radars operating at shorter wavelengths (X- and K-bands) have also been utilized, including those with multiple polarization and Doppler capability [30]. For propagation modeling, this is virgin territory with no adequate models and very little data.

Spectral Bands Above 17 GHz

The congestion of the spectrum for radio communications will inevitably push some services to bands beyond 17 GHz, the K_a-band and above. Radiowave propagation at frequencies above 17 GHz

⁵ C-band refers to frequencies between 4 and 8 GHz.

Location	CCIR rain zone	Latitude (north) degree	Longitude (west) degree	Azimuth from north degree	Path EL degree	Slant range km
Vancouver, BC	D	49	123	150	38	38777
Ft. Collins, CO	E	40	105	173	43	37654
Fairbanks, AK	C	65	148	129	9	40905
Clarksburg, MD	K	39	077	214	39	37971
Las Cruces, NM	M/E	32	107	168	51	37075
Norman, OK	M	35	097	184	49	37242
Tampa, FL	N	28	082	214	52	37060
Montreal, PB	K	45	074	215	31	38583
Montreal, PB	K	46	075	214	31	38562

■ **Table 1.** NASA Advanced Communications Technology Satellite (ACTS) program propagation terminal sites.

is plagued with rain-induced signal attenuation, a factor that for small probability levels can be very large. Therefore, services that require a low to moderate degree of link availability are likely to be attracted to frequencies above 17 GHz sooner than those demanding a very small probability of outage. The aeronautical mobile satellite service can use the K_a -band to its advantage considering that the cruising altitudes of most flights are high enough to either eliminate or considerably reduce the rain attenuation problem. Links in parts of the world with a low annual rainfall can use frequencies above about 17 GHz without significantly compromising link availability. For example, feeder links of mobile satellite systems can be placed in the relatively dry regions of the country to minimize rain attenuation at frequencies above about 17 GHz.

Link availability can be improved via the use of some form of fade mitigation technology. Hence, if tools to offset rain-induced effects are employed, the K_a -band can be used for services that require a moderate degree of link availability but cannot afford a large power margin. The VSAT industry is showing much interest in the K_a -band. A low-margin VSAT can transmit in the K_a -band by either reducing its demand on link availability or employing a fade mitigation technique.

ACTS Propagation Campaign

To accommodate low-margin systems, propagation research in the U.S. includes a measurement campaign using NASA's Advanced Communications Technology Satellite (ACTS) [31]. An experimental spacecraft, ACTS, provides transponders and propagation beacons at 20- and 30-GHz bands. ACTS will also be used for K_a -band mobile/personal experiments. Plans for future research at the K_a -band call for the expansion of the current knowledge on K_a -band propagation with a focus on these efforts [32]:

- Development of attenuation prediction models for atmosphere-induced effects with attention to high-occurrence, low-attenuation factors, such as light rain, clouds, and fog.
- Refinement of the existing climatological maps.
- Development of fade mitigation methods.

- Development of a model for large-scale diversity.
- Providing a means of real-time frequency scaling of propagation impairments.
- Investigation of propagation characteristics of land, sea, and aeronautical mobile channels.
- Development of models for predicting impaired operation and outage duration statistics and the mean time between outages or impairments during a rain event.

The measurement phase of the ACTS campaign is likely to last four years, with a total campaign period of five years, 1993 to 1998. Several sites, all equipped with dual-frequency beacon receivers and radiometers, will collect data. Considering the complexity of the campaign, much thought has been given to data archiving logistics. Data archiving and dissemination will occur in a single organization, known as the ACTS Propagation Data Center, located at the University of Texas, Austin [33]. The ACTS propagation measurement sites are shown in Table 1.

Because the ultimate goal is to provide design tools for system engineers, the ACTS campaign emphasizes interaction between the experimenters and industry. A forum known as the ACTS Propagation Studies Workshop, formed in 1990, annually brings together experts from industry, academia, and elsewhere to develop plans for the ACTS propagation campaign [34].

Regulatory Issues

The increased use of satellites by today's emerging services will lead to new demands for the already scarce resource of the radiowave spectrum. These demands will inevitably result in a more aggressive approach by the ITU toward revising existing allocations and generating new ones. Therefore, regulatory bodies around the world will need propagation data even more than before. Hence, future propagation research should support regulatory organizations with emphasis on:

- Active participation in the efforts of the ITU's Radiocommunications Sector, particularly Study Group 5 (recently merged with Study Group 6, renamed Study Group 3).
- Support of the ITU in providing spectrum for services that employ satellites for communications.

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- Cooperation with other regulatory organizations, such as the National Telecommunications and Information Administration (NTIA), Federal Communications Commission (FCC), Space Frequency Coordination Group (SFCG), and Consultative Committee on Space Data Systems (CCSDS).

ITU Radiocommunications Sector Study Group 5 specializes in propagation in nonionized media. The activities of this group entail mainly the development of recommendations for predicting propagation anomalies in communications systems. Many of these recommendations can be expanded to better serve system and design engineers. In particular, recommendations dealing with propagation in mobile satellite channels (Rec. 680, 681, and 682 [13]) can benefit from propagation research. These recommendations would be enhanced, for example, by providing prediction models for signal attenuation, depolarization, and delay spread at all bands of interest with the elevation angle and the antenna type as parameters.

The inclusion of environmental descriptors in a model for mobile/personal applications is an important factor in the successful use of a prediction tool by system engineers. Examples are the terrain type in land applications, the state of the sea surface in maritime applications, and the cruising altitude in aeronautical applications. More work by ITU members to develop meaningful, easy-to-use environmental descriptors is needed. Furthermore, Radiocommunication Sector recommendations should be expanded to include models that accurately predict the propagation phenomena for the application of interest at the coverage of interest. Future efforts should include nongeostationary configurations in addition to the GEO systems.

To predict slant-path rain attenuation, the Radiocommunication Sector provides prediction models and rain climate maps. These rain climate maps are in need of improvement; for example, the map for the U.S. places New Mexico, with its arid climate, in the same rain climate region as South Carolina, which has subtropical weather. Clearly, future propagation research should correct such discrepancies [23].

Microclimatology is an important factor in the design and planning of fixed and broadcast services. Radiocommunication Sector models are generally too crude to account for this effect and hence give rise to prediction inaccuracies. Examples include errors in estimating link availability for areas prone to microclimatological effects when prediction models are used. This problem can be remedied by observing climatic statistics at a higher special resolution than has previously been done, when potential for microclimate exists. This topic needs to be addressed by propagation researchers, and the resulting data should be provided to the Radiocommunication Sector.

Data Dissemination and Representation

Today's sophisticated satellite networks require automated techniques for link calculation and planning. Propagation prediction tools should be presented to system engineers in an intelligible, easy-

to-use format. To save time, data and models should be incorporated with computerized link calculation programs. Therefore, the propagation community should provide engineers with user-friendly propagation software that can be easily implemented on personal computer systems and readily interfaced to the user's design control tables [35].

Simulation techniques are playing an increasingly important role in the planning, design validation, and implementation of communication systems. Because the collection of propagation data is often a time-consuming effort, an alternate approach may be needed to meet the propagation needs of a system under design. In such a case, simulation can be an attractive alternative, assuming that adequate prior data can be applied to the system under consideration. Schemes to simulate propagation effects need to be developed and provided to system designers. Again, to enjoy widespread acceptance, a simulation tool should use modern software technology and be capable of running on a personal computer.

Handbooks are useful tools for educational and system design purposes. In the United States, NASA has published two handbooks on slant-path propagation effects [36, 37]. NASA handbooks have been used by U.S. industry for many years. Radiocommunication Sector Study Group 5 is also working on a handbook to complement some of its recommendations. Such handbooks would be frequently updated in order to ensure their utility and vitality.

Conclusions

Areas in need of further research include the following:

- Mobile/personal links in all the ITU-allotted bands, including the relevant choices of the propagation environment, ground antenna type, and satellite orbit configuration as parameters.
- Rain climatology, including microstructure and seasonal effects.
- Rain attenuation models, including event duration distributions.
- Fade mitigation technology.
- Cloud effects for frequencies above about 30 GHz.
- Bands above about 17 GHz, with emphasis given to low-margin applications.
- Low-latitude ionospheric scintillation effects for lower frequency bands (direct broadcast and aeronautical applications).
- Spectrum allocation for satellite applications via participation in regulatory processes.
- Computerized models for the prediction of propagation effects.
- Tools for the simulation of propagation effects.
- Maintenance and periodic revision of handbooks on slant-path propagation

The propagation community must stay abreast of the changing trends in the satellite communications market. This can be achieved by an ongoing dialogue with system planners and design engineers of satellite communication networks. The success of propagation research in the future will depend largely on how well the needs of the systems and engineering community are communicated to the propagation experts and experimenters, and how effectively the propagation community responds to new challenges.

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Biography

FARAMAZ DAVARIAN received his Ph.D. degree in electrical engineering from the University of Southern California in 1975. After graduation he began his career by teaching at the College of Science and Technology, Narmak, Iran, from 1976 to 1979. He was with Lincom Corp., Los Angeles, from 1979 to 1982. He joined the Jet Propulsion Laboratory (JPL) in 1982 to work on the Mobile Satellite (MSAT) Project. His main areas of contribution were propagation, channel simulation, modulation, and systems engineering. During that period, he was awarded three technology patents. Since 1986 he has been a part-time faculty member in the engineering department of Loyola Marymount University, Los Angeles, where he teaches graduate courses in communications. He currently supervises the spectrum engineering group and manages the NASA Radio Wave Propagation Program at JPL. As the propagation program manager, he has initiated a number of studies and experiments to improve knowledge of radio wave propagation in satellite communications.

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